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INDUCTION HEATING ADVANCES: APPLICATIONS TO 5800° F

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By

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Foreword

Induction heating has extended the range of technologists' capabilities in many areas. This source of energy is often limited only by the methods of insulation and required handling of the heated parts.

This report discusses advances in the use of induction heating at higher temperature, as developed at the NASA Lewis Research Center, Cleveland, Ohio. It was prepared by A. F. Leatherman and D. E. Stutz of Battelle Memorial Institute, Columbus Laboratories, for the space agency's Office of Technology Utilization and draws from the knowledge and experience of the authors as well as NASA personnel. It is one of a series of publications intended to help persons who are not engaged in aerospace work benefit from the advances in technology resulting from such work.

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Contents

Introduction

For several years, NASA technologists at the Lewis Research Center in Cleveland, Ohio, have been accumulating valuable experience in the practical use of induction heating. Many of the Lewis applications are vastly more demanding than most of those in industry. Some of these demanding applications have become routine for the Lewis people. The purpose of this publication is to provide a useful reference document for industry by describing valuable features of the Lewis knowledge and experience in induction heating and noting the advances that have been made.

The Lewis staff now routinely brazes complex objects in a versatile and practical vacuum induction furnace of Lewis design. Practical induction heating of solid materials to temperatures above 5800° F has been achieved in other Lewis furnaces. There is no intent to represent all such Lewis achievements as unique technology. Others may have practiced many of the same applications. However, practical descriptive data to aid in the design and construction of high-temperature induction heating applications such as these have not been widely published. The Lewis experience, cutting across several technical areas, provides a body of knowledge in a rare combination, all of which is potentially useful for industrial purposes.

One aspect of the experience in the Lewis Laboratories, which is worthy of emphasis, forms an underlying current throughout the following pages. Many of the examples described here started with what would normally have been considered good design of an induction heating setup. However, because of the demands of the Lewis work it was necessary to obtain higher temperatures and faster rates of heating than normally expected of an induction heating system. Meticulous attention was applied to each part of the system and this led to major improvements in operation and performance previously unobtainable with the Lewis equipment. This shows that devoting careful attention to each component of the induction heating system may eliminate inefficient features and produce more substantial improvements in performance than were expected. The importance of providing suitable attention to each aspect of an installation cannot be over-emphasized. Improvement often can be realized without complicated or expensive steps by applying simple knowledge based on a good understanding of induction heating technology.

The heating applications cited as examples here are through-heating and vacuum brazing, in which motor-generator power supplies are employed. However, the principles and innovations discussed are useful for other types of equipment and for other types of induction heating such as heat treating or melting.

To supplement the logical explanation of these innovations and practical guidelines, the appendix contains a discussion of basic principles of induction heating and some detailed discussions of impedance matching that one does not generally find in the literature. From this presentation the user may be able to determine the means to improve the efficiency and performance of his heating arrangement even though it may differ in some respects from the examples used here. For the person who wishes to become exposed to induction heating technology and principles in greater depth, several good sources of information on equipment, applications, and design calculations are listed.

Induction Furnace Design and Construction

The term "induction furnace" means different things to different people. As used here, it includes the work coil, the support for the workpiece, the insulating and hermetic chamber in which the heating takes place, and auxiliary equipment such as viewing ports, thermocouples, and protective atmosphere supply. In other words, it is the portion of the installation that contains the work to be heated. Careful attention to detail yields designs which produce substantial benefits in greater speed of heating, a higher temperature limit, greater ease of loading and unloading, reduced contamination, and lower cost.

It will not be feasible to present here a complete instruction manual on furnace design and construction. However, important principles and several examples of furnace designs will be presented and discussed. The examples will include one design that has been used successfully at Lewis Research Center for preheating refractory metal alloy billets regularly at 5000° F. By adding radiation shielding, a similar design has made a temperature of 5850° F attainable. A successful furnace for vacuum brazing at temperatures in excess of 2000° F will also be described. The designs worked out by the Lewis people should offer many helpful hints to others working in high-temperature technology.

FURNACE PRINCIPLES

The furnace for high-temperature work is designed primarily to reduce heat losses sufficiently so that the desired temperature can be reached without excessive power requirements. It must also protect the workpiece from oxidation and from contamination, permit monitoring of temperature, and provide rapid loading and unloading if the workpiece is to be further processed in the heated state.

A workpiece mounted in a furnace is subject to heat loss by three mechanisms: (1) radiation to the surroundings, (2) convection loss, unless the furnace provides a vacuum environment for the work, and (3) conduction loss to the support and surrounding gases, if present. Of the three, radiation loss is usually considered the most important

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(ref. 1). However, convection loss can also be very high, especially when a protective atmosphere is used that has high heat-transfer properties such as hydrogen or helium. Mechanical arrangements usually can be made to maintain very low conduction losses. Convection losses essentially do not occur if the workpiece is heated in vacuum. Induction heating is particularly advantageous for use in vacuum since heat can be generated in the work without contact by gas or mechanical structures. However, because of the time involved in assembling and disassembling a high vacuum setup, protective-atmosphere furnaces are widely used. Protective-atmosphere furnaces permit rapid removal of work at maximum temperature.

Radiation losses are reduced considerably by the use of reflecting surfaces located so as to return much of the radiation to the work.

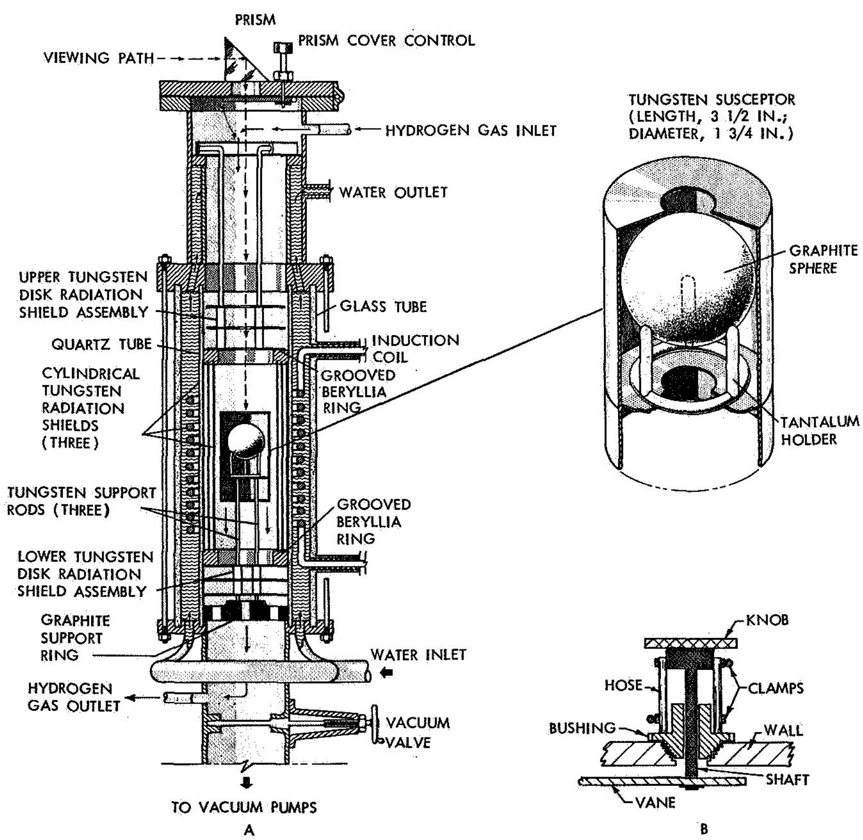

FIGURE 1.—Schematic view of (A) induction furnace and (B) hose device for vane.

Polishing of the inside surfaces of the coil, and even gold plating them, can aid significantly in the reflection of radiation. A white insulating coating on the coil turns can also serve effectively as a reflector. Separate metal foil structures called radiation shields are also widely used. The following examples will illustrate Lewis design practices for several furnaces of the vacuum and protective-atmosphere types.

VACUUM REACTION FURNACE

The furnace design illustrated in figure 1 was used in research at Lewis to investigate rates of hydrogen-graphite reaction at temperatures up to 4100° F (ref. 2). The furnace is capable of operation under vacuum as well as with a protective or reaction gas atmosphere.

Susceptor

The workpiece in the form of a graphite sphere was heated by means of an intermediate cylindrical tungsten "susceptor." The term susceptor applies to an intermediate body which becomes induction heated and then transfers its heat to the workpiece by radiation and convection. With this approach, various workpieces can be heated that might not otherwise heat by direct induction. In the example, the graphite sphere was too small for induction heating at maximum efficiency with this combination of frequency (10 KHz), resistivity (1000 microhm-cm), and diameter (1.5 inch). Also, when using a cylindrical coil, more uniform heating of the sphere could be obtained by means of the susceptor. When the ratio of specimen size to skin depth of induced currents is sufficiently large however, graphite heats very efficiently by induction heating (see Appendix for discussion of principles).

Chamber and Coil

Temperature is measured optically in this furnace through a prism and a series of holes in the radiation shields and susceptor. The prism serves as a part of the wall of the furnace chamber as well as a mirror. A vane is provided to cover the lower face of the prism except when an observation is being made. Otherwise, gaseous products from the workpiece can cause clouding of the prism surface when vacuum is used. The cover vane swings out of view during an observation. When protective gas is used in the furnace instead of vacuum, the fact that the gas is introduced just below the prism helps to prevent clouding since the motion of the clean supply gas tends to sweep the chamber clean. It is difficult, if not impossible, to obtain temperature readings in the presence of metallurgical "smoke."

A convenient scheme was used at Lewis to make a good vacuum seal around the shaft for the prism cover vane, and serve as a return spring at the same time. As shown in figure 1B, the method used was to clamp one end of a few-inch piece of rubber vacuum hose to the shaft and clamp the other end to a bushing that is threaded or welded into the chamber wall and through which the shaft passes. The hose is clamped in place with the vane in closed position. The return-torque feature returns the vane to closed position after an observation has been made.

In the example of figure 1A, the work coil is submerged in water which cools the coil as well as the wall of the furnace.

SUSCEPTOR CUP AND SHIELDING DESIGN

The Lewis furnace unit of figure 1A employs a tungsten susceptor unit and radiation shields mounted in place with the aid of grooved ceramic rings. This type of construction is often preferable for temperatures up to 4500° F. Above 4500° F, all-metal designs for the shielding and susceptor are preferred.

NASA Tech Brief 66–10538 (ref. 3) explains one style of all-metal susceptor and shielding design that can be used with various induction furnaces operated at 3000 or 10 000 Hz. Figure 2 illustrates the

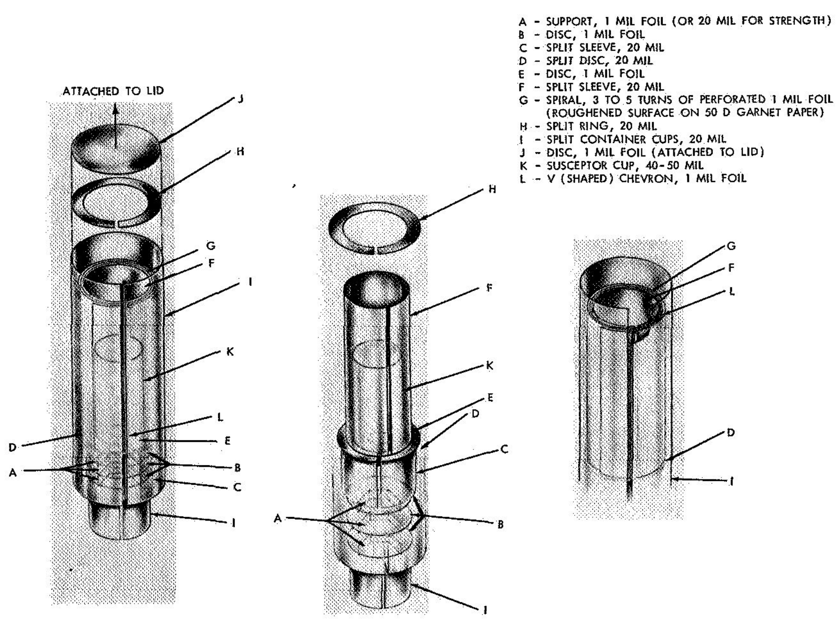

FIGURE 2.—Tungsten insulated susceptor cup unit for high temperature (5000° F) induction furnaces (Metilur assembly).

The Metilur, "Materials Experimental Tungsten Induction Laboratory Unit Replacement," is an improved simple design of susceptor cup plus shielding using only one type of material of construction (tungsten) and thereby relieving a possible contamination problem. The unit shown in figure 2 consists of the susceptor cup, side and bottom shielding, and support containers. Top shields (usually mounted to the access lid) are positioned after specimens are placed in the susceptor cup, which has previously been lowered inside the work coil of the induction furnace.

Use of thin tungsten foil enables the Metilur to perform with high efficiency. Its electrical resistance is high enough to reduce electrical conduction. This, combined with its thinness, results in negligible electrical losses in the foil.

The Metilur assembly is easy to install or remove. The design is easy to standardize and adapt for interchangeability of parts. Therefore, a unit can be borrowed from another chamber or spares kept for quick replacement. The design has been arranged to avoid hot spots or arcing. One type of research being accomplished with such an assembly is cycling runs. One cycle consists of the following steps: With the power settings pre-set, the "on" button is pressed and in one minute the specimen is at 4730° F—in hydrogen. After 10 minutes, at temperature, the power is shut off and the unit rapidly cools down to room temperature. The total cycle is about 22 minutes. This cycling has been found to produce no detrimental effects on furnace, susceptor, or shielding.

The Metilur assembly, void of toxic beryllia or thoria, is also versatile. The inner parts can be reduced in number or thickness to make more room for larger susceptors and billets. In heating a billet, the susceptor is not necessary. The perforated tungsten foil shielding can be placed around the billet or susceptor and will function without the split cup assembly.

LAMINATED RADIATION SHIELD DESIGN

Another Lewis radiation shield of a slightly different design may be of interest for some applications. The design referred to is described in NASA Tech Brief 65–10188 (ref. 4). Figure 3 illustrates the construction.

The objective was to reach at least 5500° F in a vacuum induction furnace the cylindrical interior of which measured 3.5×8.0 inches. Experience has shown that without a special shielding design more efficient than even the Metilur, the maximum temperature would be limited to about 4000° to 4500° F due to excess heat generation within the thermal barriers by electrical induction. Tungsten with its melting point near 6100° F was used in the special design shown in figure 3.

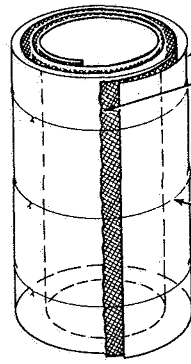

FIGURE 3.—Laminated shield.

Although fabrication of tungsten is not extremely difficult, care is required in handling it. Tungsten is brittle at room temperature, and fabrication requires special techniques, experienced personnel, and often special machines and tools. If heated above the recrystallization temperature by any means, the tungsten or fabricated joint can become extremely brittle when cooled again.

The basic heat radiation shielding developed at Lewis for this application consists of refractory metal foil laminated or alternated with clean refractory metal fine fibers (see fig. 3). The fibers are installed in the form of a loosely packed fibrous mat. The laminations of foils and fibers can be wrapped concentrically in a cylindrical or spiral shape to the desired thickness and banded on the outside by thin wires of the same material.

To reduce the transfer of heat, this innovation makes use of the principle of multiple radiation barriers. The problem of electrical induction within the shields is solved by creating a high circumferential electrical impedance. Therefore, the thinnest foil and the lightest possible fiber-packing should be used to minimize the amount of heating in the induction field. Since the electrical resistance of tungsten increases with temperature, whatever heat is generated within the shielding will tend to be self-limiting. In addition, loose packing of the fibers should reduce the thermal conduction between the shields.

This shielding has proven its ability to insulate an extremely hot, inductively heated specimen. It was tested in a vacuum induction furnace producing a final temperature of 5850° F on a tungsten specimen, 2 inches in diameter and 6 inches long, enclosed by the shielding.

Advantages derived from this shielding over other conventional insulations are:

(1) The thinness of the shields (foils) prevents or reduces self-electrical heating in an induction field

(2) The method of construction achieves an assembly of multiple radiation barriers in a minimum of space. This compactness is important in increasing the efficiency of induction coils by making possible closer coupling

(3) The innovation eliminates the need for ceramics as part of the shielding system

(4) The foil and metal fiber construction makes it very light in weight

(5) Because of its simplicity, the shielding can be fabricated very easily by inexperienced personnel, without special tools or equipment

(6) The low bulk density of the shielding reduces the thermal inertia for faster heat-up and cool-down time

(7) It can be temperature-cycled rapidly without high thermal stress

(8) The shielding concept is not restricted to furnace use. It can be used for other applications, such as insulating high-temperature gas ducting, etc.

(9) The shielding has a relatively short outgassing time when used in vacuum furnaces

(10) It permits a wide choice of materials—metals like tungsten, rhenium, tantalum, molybdenum, or any other material that can be made into thin, flexible sheets

(11) It can be used in vacuum, inert, or reducing environments, in air at reduced temperature, or at higher temperatures in air if made of noble metals

(12) It can be fitted around contours of most any shape

(13) It is more economical in material and labor cost than conventional shielding for applications in this temperature range.

PROTECTIVE-ATMOSPHERE FURNACES

In some applications, such as where it is desired to remove a heated billet quickly from an induction preheating furnace, the complications of a vacuum-type furnace design to permit this removal may not be warranted. The Lewis staff has successfully employed protective-atmospheric-type furnaces for such applications. Billets preheated to 5000° F for extrusion have been removed from the furnace of figure 4 (ref. 5) in 1½ seconds, placed in the extrusion equipment and extruded in a total of 2½ to 5 seconds. The support pedestal for the billet drops, bringing the billet with it. While in closed position, the pedestal seals against the wall of the chamber.

Even though rapid removal of the workpiece is not required, the protective-atmosphere type of furnace may be lower in cost or easier to construct than a good vacuum furnace, assuming that sensitivity of

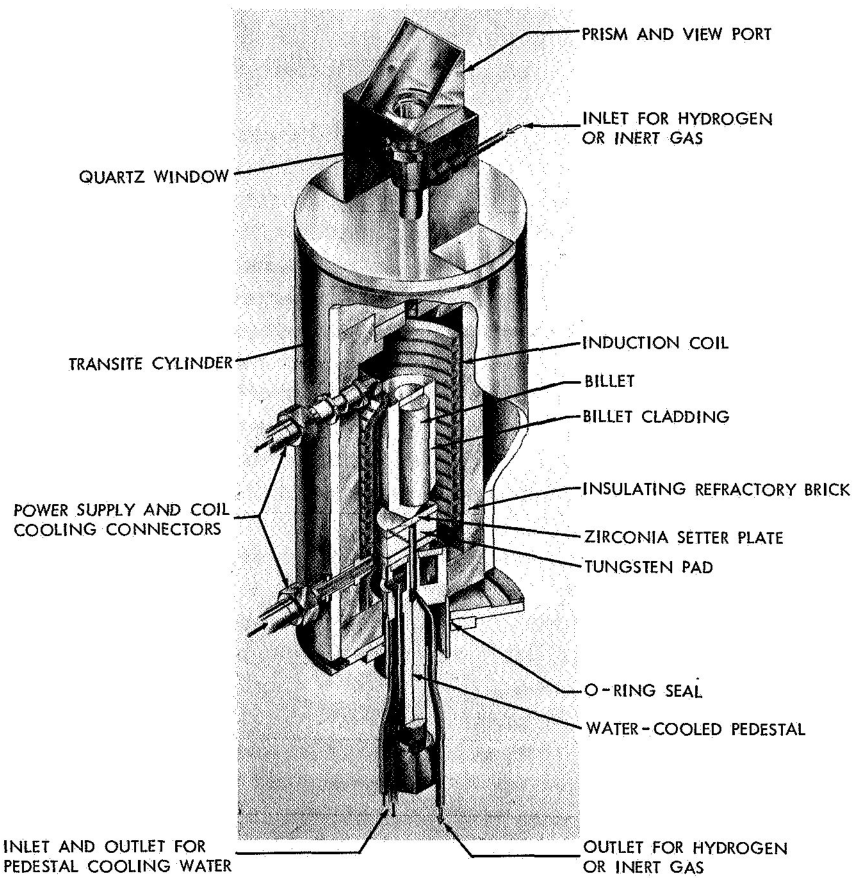

FIGURE 4.—High-temperature, hydrogen atmosphere, extrusion preheat furnace.

the work to contamination does not require vacuum. Comparing some of the construction features of figures 4 and 1A, it is noted that a Transite® liner suffices for the atmosphere furnace whereas water-cooled quartz is used for the vacuum type. Refractory brick insulation or bubble zirconia can be used as a spacer in the atmosphere furnace but will release too much gas in a vacuum. Radiation shields could be used in the atmosphere furnace to increase the upper temperature limit. The prism viewing technique is used in both cases with the gas introduced into the atmosphere furnace near the prism to sweep vapors away from the prism surface. A prism cover is not used with the atmosphere furnace.

Figure 5 (ref. 6) illustrates a protective-atmosphere furnace including radiation shielding and a susceptor cup. The furnace is pow-

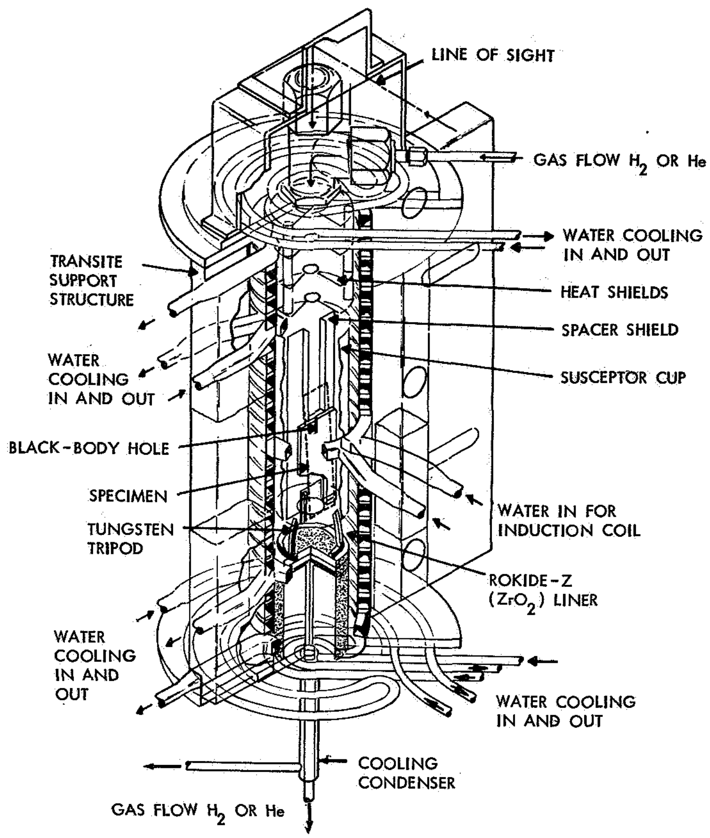

FIGURE 5.—Protective-atmosphere furnace.

ered by a 75-kw, 10-kHz generator. The coil is made from ⅜-inch-square copper tubing with 0.032-inch wall. Approximately 29 turns are wound overall and cut into four sections which are later reassembled. The 15-turn section at the center is energized by the induction equipment. Four water circuits are used for the coil. Partitions are assembled into the cross-section of the tubing to separate the four water circuits. The turns are spaced 1/16-inch apart and separated by brass pins brazed to the outside surfaces of the tubing. These pins are inserted into properly spaced holes in the insulating (asbestos composition) support structure. The space between adjacent turns is filled with a castable zirconia. The exterior surface of each turn facing the support structure is insulated with a thin layer of castable zirconia and a 0.75-inch layer of alumina, and the entire outside surface of the cylinder formed by the coil assembly is sealed with fiber glass impregnated with an epoxy resin. The surfaces of the turns facing the center

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of the furnace are sprayed with zirconia to a depth of 30 mils, using rod-flame spray apparatus. A prism and viewing port for optical pyrometry are provided at the top of the furnace.

Notes:

(1) This induction furnace will heat up from room temperature to 4750° F in about 30 seconds and cool down to room temperature in about 2 minutes, depending upon the load material and its mass

(2) The furnace life will exceed 100 hours at an operating temperature of approximately 5000° F, using a purified-hydrogen flow rate of 10 to 40 cubic feet per hour

(3) By replacing the inside zirconia liner with a high-temperature radiation shield or refractory thoria, operating temperatures of approximately 6000° F can be achieved

(4) Engineering drawings are available from Lewis Center for the construction of this furnace.

VACUUM BRAZING FURNACE

Brazing as a fabrication procedure permits the assembly of relatively large and complex pieces from small ones which can be more easily machined. In this manner complex shapes can be made up with an advantage over casting for runs of a few parts of a given shape. Vacuum brazing provides high-quality, bright joints without the dangers involved in using hydrogen.

A vacuum induction brazing furnace designed and used at Lewis Research Center employs an induction-heated graphite susceptor as the source of radiant energy to heat parts inside it. The susceptor approach permits a wide variety of sizes and shapes of parts to be brazed that might otherwise have been difficult to process by direct induction heating.

The rate of *heating* of the furnace can be fast or slow depending on what power setting is used for the induction equipment. Either a slow or fast *cooling* rate can be obtained depending on (1) whether insulating material is placed around the susceptor or (2) it is permitted to cool by radiation directly to the furnace wall. The slow cooling rate (one brazing cycle per day) permits excellent temperature control and uniform temperature distribution in the part, thereby achieving minimum distortion. The fast cooling rate (up to 300° F per minute) is beneficial for obtaining fast solidification of the braze alloy with minimum time above the melting point in case a problem exists concerning compatibility of the braze alloy and parts to be joined.

The Lewis brazing furnace (ref. 7) uses a 100-kw generator at 9600 Hz to heat the graphite susceptor. Temperatures of 2400° F are easily obtained with a graphite susceptor 15 inches I.D., 18 inches O.D., and 20 inches high. Degradation of the insulation precludes higher temperatures with this susceptor. By using a 6-inch-diameter susceptor to reduce radiation loss and eliminate the need for insulating materials, temperatures of 4500° F have been obtained. The furnace chamber is constructed of ½-inch thick 304 stainless steel, 42 inches in I.D., and 54 inches high, with a removable lid that swings out of the way for access. A photograph of the unit is presented in figure 6 and a sketch of the susceptor and interior assembly is presented in figure 7. The specimen holder can assume a variety of designs to suit the workpiece.

A lid for the susceptor cup has been constructed of a sandwich consisting of a layer of Fiber-frax® between two stainless steel screens. Sheets of graphite fabric and Fiber-frax® between the susceptor and coil provide thermal insulation when the slow-cool cycle is in use. Spun glass can also serve well to protect feed-throughs and fittings from direct radiation. Commercial O-Ring seals can be used against the furnace shell.

The coil for the 18-inch susceptor has 16 turns, is 24 inches in

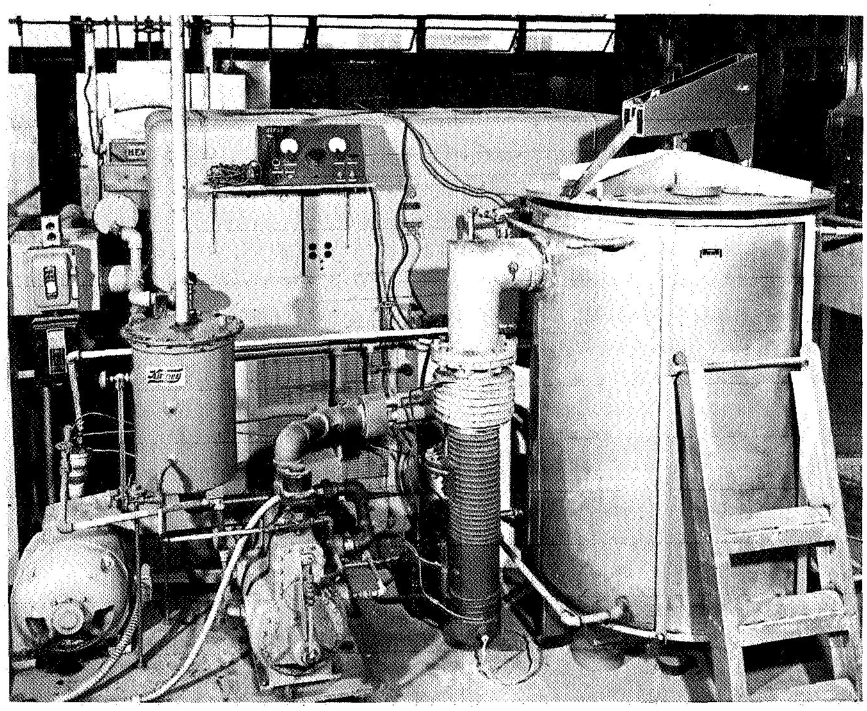

FIGURE 6.—Photo of vacuum furnace and equipment.

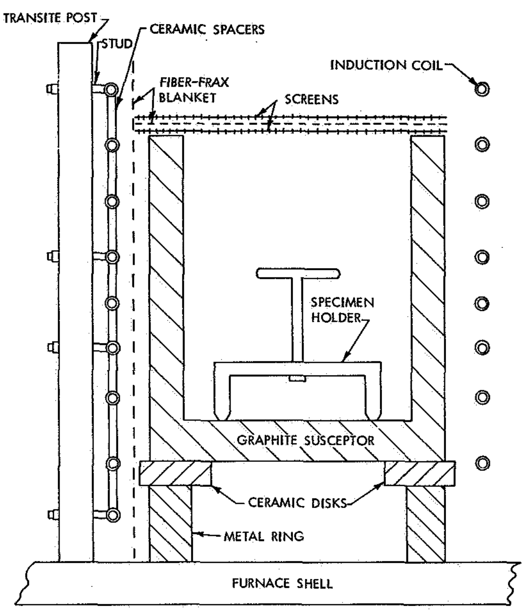

FIGURE 7.—Vacuum brazing furnace.

diameter, and is constructed of 1-inch copper tubing. The coil is supported by studs silver-soldered to the turns and bolted to Transite® posts that have been insulated against moisture. In constructing some of the coils, studs have been used only one every sixth turn with the intermediate turns supported by spacers of ceramic tubing which have each end ground to a radius to fit the copper tubing.

Difficulty will be encountered occasionally in vacuum brazing from gaseous discharges that take place between internal members. Lowering the pressure to a harder vacuum will often relieve such discharges. At pressures as high as 50 microns with a bare copper coil in the furnace, it has been found necessary to limit the coil voltage to 175 volts. Other steps to rectify the problem include the use of fewer turns more widely spaced in the coil, and operating the equipment so that the load impedance is less than the normal optimum to provide full rated output current from the generator for something less than full rated voltage.

Bright brazing of stainless steel is realized in the pressure range of 2 to 10 microns (2 to 10×10^{-3} Torr). This range is low enough to discourage gaseous discharge but high enough to limit vaporization of braze alloy constituents. The latter problem can be avoided by using alloys which have low vapor pressures (available at a higher price). A pressure of 3 microns (3×10^{-3} Torr) in vacuum brazing is equivalent to better than a $-70°$ F dew point in hydrogen brazing.

Temperature measurements are made optically through a quartz window outfitted with a cover vane inside the chamber. The vacuum-hose spring return idea described earlier is employed on the vane control shaft.

Some metals that require a harder vacuum such as columbium and tantalum have been brazed by sealing the parts in cans made of Inconel® or stainless steel. The cans are evacuated to 10^{-5} or 10^{-6} Torr prior to sealing. The sealed cans are then processed in the furnace at the normal vacuum condition.

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APPENDIX

Basic Induction Heating Principles

GENERAL CONSIDERATIONS

Induction heating is one of three methods of using direct dissipation of electrical energy to heat the work material. The other two are resistance heating, where physical contact is made with the workpiece, and dielectric heating, in which heating of electrical nonconductors is achieved by the power loss developed in an alternating electric field. All three are used in industrial processes.

Induction heating provides a means for precise heating of electrically conducting objects. In some cases, it is the only practical method of supplying heat to the work material. Induction heating is clean, fast, repeatable, and lends itself to automatic cycling.

Some of the more important advantages of induction heating are:

(1) No contact is required between the work load and the heat source

(2) Very high temperatures can be produced

(3) Rapid heating of the workpiece is easily achieved

(4) Control of processing and production is simplified

(5) Higher efficiency than that offered by many furnace methods can be realized

(6) Heating is adaptable to production methods

(7) Heat generation can be restricted to a surface zone of the load

(8) Heat may be restricted to localized areas

(9) Working conditions are cooler and cleaner

(10) Vacuum or controlled atmospheres may be used to protect the workpiece.

Induced Currents and Skin-Effect

Induction heating occurs when electrically conductive materials, such as metal workpieces, are immersed in an alternating magnetic field. This field is usually produced by an electrical coil energized by a suitable source of ac electrical energy. The ac magnetic field induces voltages in the conductive material and these voltages cause circulating currents (eddy currents). It is customary to refer to these currents as "induced currents," although only the voltage is actually "induced." The magnitude of the induced currents is determined by the effective magnitude of the induced voltage and the impedance of the workpiece. The flow of induced current generates I^2R losses and heat in the workpiece. Additional heat is produced in magnetic workpieces as the result of hysteresis losses; this heat is usually small, but, in some cases involving strong magnetic fields, heat resulting from hysteresis losses can become significant.

Induction heating is efficient and practical if certain basic relationships dealing with the frequency of the magnetic field and the properties of the workpiece are satisfied. Although the relationships are not sharply critical, they must be satisfied to the extent that a suitable degree of "skin-effect" is produced in the workpiece. Skin-effect is the phenomenon by which the currents flowing in the workpiece tend to be most intense at the surface, while currents at the center are near zero. As a consequence of this distribution, the currents produce a greater rate of heating near the surface. Skin-effect is present in every successful induction-heating application. Information that will help in determining if sufficient skin-effect is being achieved in a given application is given in the next section.

Since the heat is generated in the outer portion of the workpiece, for through-heating one must allow a little time for the heat to be conducted to the center of the work. However, the depth of the surface zone containing the concentrated current can generally be as much as one-fourth the diameter of the piece without serious loss of efficiency. The heat travels rapidly into the interior, making induction through-heating much faster than any other practical nonelectrical heating method. On the other hand, by using a higher frequency and enhancing skin-effect, one can surface harden steel parts without affecting the core structure.

Consideration of Operating Frequency

Consideration of the operating frequency should be the first step in the design of a successful induction heating installation.

In order to achieve efficient induction heating, one must arrange for a proper ratio of workpiece diameter (or thickness) to reference depth. ("Reference depth" is defined in the next paragraph.) For a given workpiece diameter, the thinner the current-carrying layer, the greater the rate of heat generation is in the surface, other factors remaining constant. Ignoring minor effects, the effective depth of the current-carrying layer depends on the frequency of the ac magnetic field, and on the electrical resistivity and magnetic permeability of the workpiece. Frequency is the only one of these factors that can be readily manipulated.

The current density in a workpiece decreases exponentially from the surface. The rate of decrease can be compared from one application to another by means of reference depth. Reference depth, which has actual physical significance in certain special cases, is defined by the formula

$$d = 3160\sqrt{\frac{p}{\mu f}}$$

where d is the reference depth in inches, p is resistivity of the work in ohm-inches, μ is the relative magnetic permeability of the work (dimensionless), and f is the frequency of the alternating magnetic field of the work coil in hertz (cycles per second).

Figure A–1 shows a graph of the reference depth versus frequency for various common metals. It can be shown (ref. A–1) that if the ratio of workpiece diameter to reference depth drops below about four-to-one, the efficiency of heating decreases. The critical frequency is defined in reference A–1 as the frequency at which the workpiece-to-reference depth ratio is 4.5 to 1 for round bars; if heating sheet

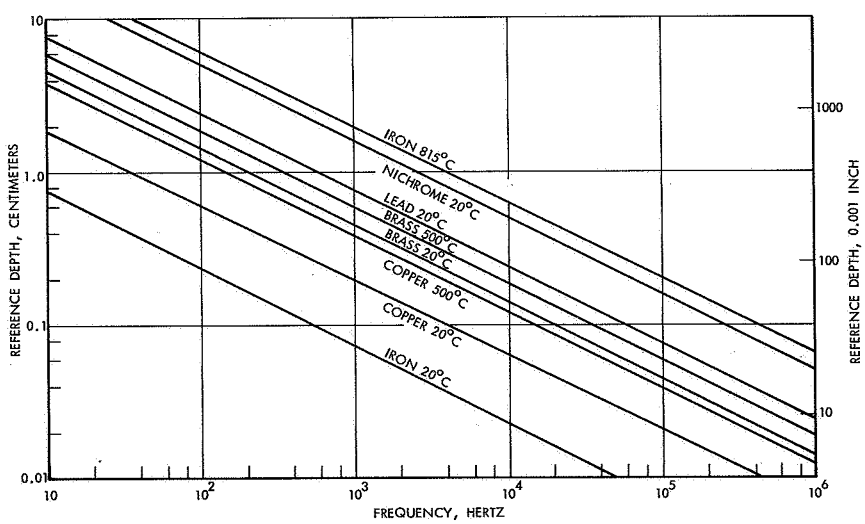

FIGURE A–1.—Reference depth for common materials as a function of frequency (ref. A–1).

from both sides, the ratio is 2.25 to 1. Figure A–2 shows the critical frequency as a function of workpiece diameter for cylindrical bars of various metals. Figure A–3 shows the efficiency of heating as a function of this critical frequency. Workpieces heated at less than the critical frequency will still heat, but at a lower efficiency.

For heating a shallow depth in a large workpiece, one selects a high frequency and does not worry about critical frequency, since the diameter will be many times the skin depth. However, for the fastest through-heating, one wants to have the zone of current flow and heat generation as deep as possible into the work so that the heat will flow to the center quickly. One then wants to choose a frequency close to the critical frequency and the calculations of reference depth and efficiency become more important.

Induction Heating Coils and Available Power

A simple solenoidal coil of one or more turns around the workpiece is most frequently used. Figure A–4 shows four basic work coil shapes: A–4A is a simple multiturn solenoid in which the load is placed inside the coil; A–4B is a modified solenoid with the ends turned up

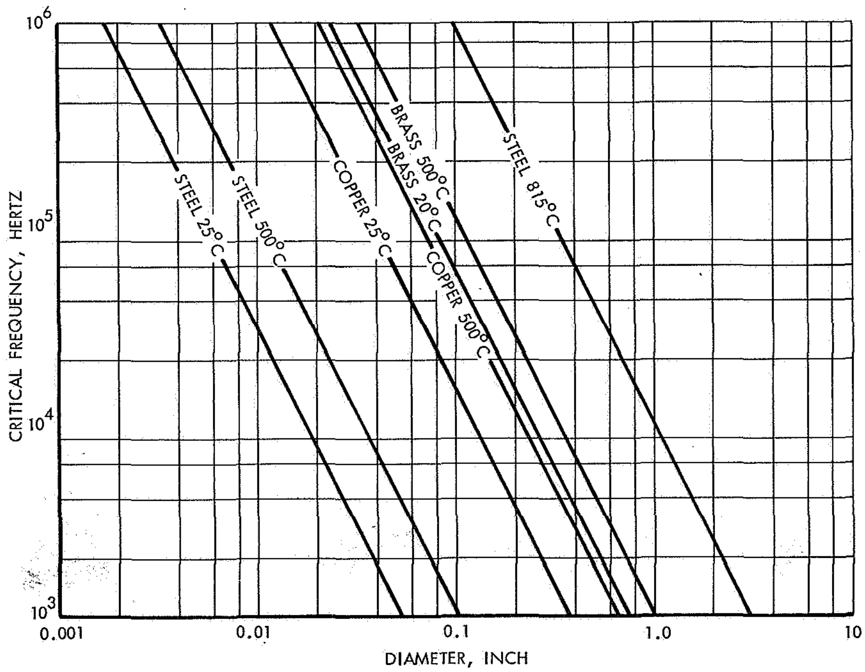

FIGURE A–2.—Critical frequency as a function of bar size (ref. A–1).

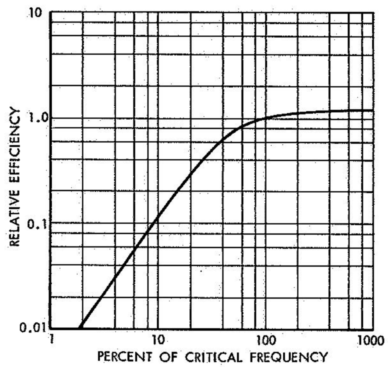

FIGURE A-3.—The relationship between relative efficiency and frequency (after ref. A-1).

(sometimes called a channel coil) so that load parts can pass continuously along the coil (horizontally in sketch); A-4C is a pancake coil for heating a flat surface from one side; and A-4D is a solenoid coil with two diameters contoured for an odd-shaped workpiece.

An induction heating coil must establish magnetic flux lines in the workpiece and this field must be powerful enough to do the job. The ability of any coil to establish a magnetic field of the needed geometry and intensity depends on the ampere-turns of the coil (coil current times number of turns), its geometry, and the magnetic circuit in which the field is to exist. Whatever the shape of the coil, all the lines of force in the magnetic field set up by the coil must pass through at least some of its turns. It follows that the most intense portion of the magnetic field is generally in the center region of the coil, and so the most effective location for the workpiece is inside the heating coil. The best example and probably the most usual application is the solenoid with a bar (workpiece) inside it. If the load cannot be placed inside the heating coil, steps must be taken to couple as much of the field to the workpiece as possible. Such schemes as putting a magnetic core in the coil to reduce the ampere-turns necessary to excite the coil and to concentrate the field as desired are sometimes used.

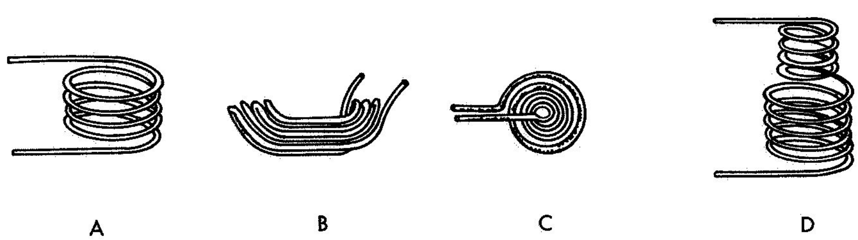

FIGURE A-4.—Example of typical work coils.

The design of coils for heating unusual shapes is to a large extent a matter of trial guided by a few basic principles. It is useful to remember that the eddy currents in the workpiece tend to be an image of the coil currents.

The direction of the magnetic field set up by the coil current is at a right angle to the current flow. The voltage induced in the workpiece by this field is maximum in a direction at right angles to the field, and therefore parallel to the flow of the original current. Consequently, the currents in the workpiece resulting from the induced voltage (induced currents) are parallel to but opposite in direction to the coil current within the limits imposed by the shape of the workpiece. (See ref. A–2).

A few simple statements can be made as guidelines concerning the ability of various coils to produce heat in a workpiece. First, the rate of heat generation is proportional to the coil ampere-turns *squared.* Thus, if one can triple the coil current in a given application, for example, he should expect nine times the heating rate without changing anything else. Second, the electrical resistivity of the work governs the rate of heat generation in it, by I^2R.

In a magnetic load, hysteresis losses are also developed which are in general negligible compared with the I^2R losses unless exceptionally strong fields are present. In heating a nonmagnetic load that has a low resistivity, large currents must be used in the work coil to achieve high heating rates. Coil losses therefore tend to be high and efficiency low when heating a low-resistivity workpiece.

In heating a copper workpiece, using a copper work coil, so long as the load and coil are at the same temperature, the maximum possible heating efficiency under ideal conditions is only 50 percent. Half the power to the coil is dissipated in it, and half in the work, assuming no other losses. As the copper workpiece begins to get warm, its electrical resistivity becomes higher than that of the water-cooled coil and the efficiency can be a little above 50 percent. Thus, good electrical conductors, such as copper and silver, make good coils but as loads are not as easy to induction heat as are other metals. Other materials such as graphite, however, have resistivity values that are almost ideally suited for induction heating. Even with loose coupling between the coil and work, graphite objects can be induction heated with coil efficiencies over 95 percent.

As discussed earlier, as the resistivity becomes higher and higher, skin depth becomes greater, and critical frequency becomes very high. Thus, it is not usually practical to try to induction heat most ceramics and other electrical non-conductors. However, some ceramic materials such as glass have high enough conductivity when hot to be heated by induction. It is important to note that in the practical viewpoint, induction heating efficiency is highest for load resistivities in a medium range and low at both the high and low extremes of resistivities.

The subject of specific calculations of work-coil parameters of solenoids and generated power has been covered extensively by several authors (refs. A–1, A–2, and A–3). Vaughan and Williamson (refs. A–4, A–5) and Baker (ref. A–6) have excellent specific treatments of this problem. The user should refer to such papers if he wishes to develop an analytical understanding of the subject or to augment the experimental approach to the application.

Determining the Power Requirement

The amount of power that will be needed for a given application is one of the major parameters to be determined. If the workpiece is regularly shaped and is to be entirely heated, the calculation is straightforward. However, if it is to only selectively heated so that the remainder of the workpiece is a heat sink for the generated heat, calculation of the power needed may be difficult. The latter case is not considered in the present discussion.

Consider a load (workpiece) to be heated throughout the entire volume. The absorbed power depends upon the required temperature rise, total weight, and the specific heat of the material. The formula for the required power to be supplied to the load (specific heat power) is

$$P_1=\frac{(W)(T)(C)}{3.412}\text{ watts}$$

where

W=pounds of material heated per hour

T=temperature rise in °F

C=specific heat in BTU per lb per °F.

To determine total input power needed from the source, the radiated power lost from the workpiece and the power lost in the work coil by I^2R losses must be added to P_1. Heat loss by convection and conduction to the surrounding atmosphere (if not in a vacuum) should also be considered. This loss is dependent upon the thermal conductivity of the atmosphere, velocity of atmosphere, and relative size factor. It is not generally practical to calculate this factor.

Radiated power is

$$P_2=5.7AE\left[\left(\frac{T_2}{1000}\right)^4-\left(\frac{T_1}{1000}\right)^4\right]\text{ watts}$$

where

E=thermal emissivity of load

T_1=surrounding temperature in °K
T_2=temperature of work in °K
A=surface area of work in square centimeters.

The radiated power varies greatly during the heat cycle because the emissivity changes with temperature and material. Typical emissivities are 0.1 to 0.2 for aluminum at 390° to 1100° F, 0.79 for oxidized steel, and 0.8 for carbon from 260° to 1100° F.

Power lost in the work coil is

$$P_3=(P_1+P_2)\left(\frac{1}{eff}-1\right)\text{watts}$$

where P_1 is the specific-heat power of the workpiece in watts, P_2 is the radiated loss in watts, and *efficiency* is the coupling efficiency of the coil. Average coupling efficiencies for close-coupled coils are given below. The total power to be supplied by the induction heating generator is the sum of P_1, P_2, and P_3.

Average Coupling Efficiencies for Close-Coupled Loads

Coil	Magnetic steel below curie	Steel above curie, stainless steel	Brass, titanium, aluminum, bronze	Copper
Helical-around work	0. 90	0. 65	0. 50	0. 30
Helical-internal	0. 70	0. 40	0. 30	0. 20
One turn-around work	0. 85	0. 60	0. 45	0. 25
One turn-internal	0. 65	0. 35	0. 25	0. 15
Hairpin	0. 85	0. 60	0. 45	0. 25
Pancake	0. 70	0. 40	0. 30	0. 20

The factors to be considered in the electrical design of an induction heating application have been briefly pointed out. Although a specific application may modify the sequence, the order of design may be as follows: First, the proper frequency is chosen for the application. Then the work coil type is selected. The power requirement is then determined as well as possible. Frequently, the next step is the determination of the number of turns necessary if the work coil is to be a multiturn coil. This calculation is somewhat involved and references A–4, A–5, and A–6 should be used for specific methods of calculating various parameters such as coil impedances, number of turns, and efficiency. In some cases, the actual calculation of these values is more time-consuming than the experimental approach. The experimental approach, weighted by experience, is most often used when the coil varies from a simple multiturn solenoid. Methods of modifying the turns of a coil electrically and of transformer impedance matching are given below in the section of this report on "Coils and Transformers," and in the "Special Section on Matching."

EQUIPMENT ARRANGEMENTS FOR EFFECTIVE OPERATION

An induction heating installation can be considered in three important parts: the electrical power source for generation of high-frequency energy, the transmission line carrying the electrical energy to the point of use, and the work coil and other equipment associated with the final transfer of the electrical energy into heat in the workpiece. Negligence in employing efficient circuit design, in equipment construction, or in apparatus design can seriously decrease the degree of success of an application. The Lewis experience has shown that in some cases where design was apparently good, special attention to all three areas has permitted further improvement. For example, a former maximum work temperature of 3000° F was raised to a new temperature limit of over 5000° F for the same workpiece by paralleling generators, using wider (lower impedance) bus bars, and by improving the coil design, as discussed later in this section. Attention to the fundamental requirements and limitations of induction heating design can remove frustrations and produce significant improvements that otherwise might never be realized.

Induction Heating Circuit Components

This section describes the main components of an induction heating installation and discusses some of the typical difficulties. Although induction heating installations are common at line frequencies on up into the radio-frequency spectrum, the installations to be considered here are in the range of 1000 to 10 000 hertz.

The three parts of an induction heating installation are shown schematically in figure A-5. High-frequency current supplied by a

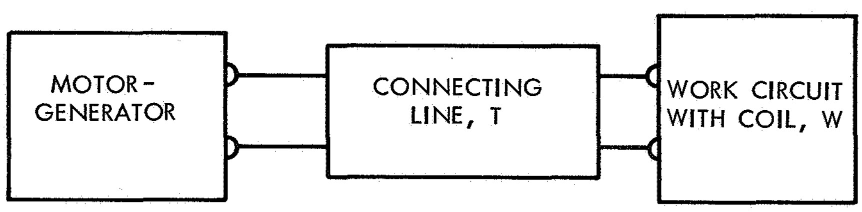

FIGURE A-5.—Major parts of an induction heating installation.

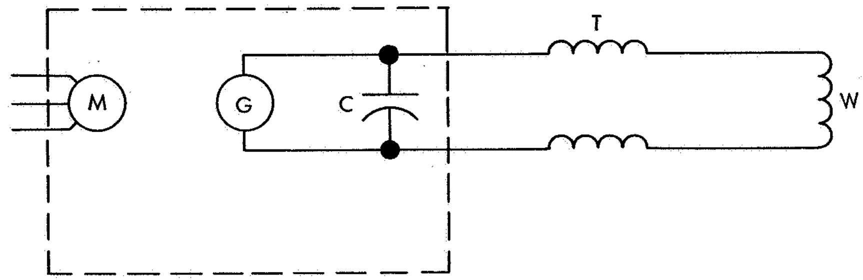

FIGURE A–6.—Possible arrangement of induction heating components.

motor-generator set is conducted to the work circuit by means of an outgoing conductor and a return conductor.

The two conductors constitute the connecting line, T. All three parts shown by the boxes may vary for different equipment arrangements. Various circuit arrangements will be discussed in the following paragraphs.

Figure A–6 illustrates one of the arrangements of components often found in small commercial induction heating units. The generator, G, is driven by a motor, M, connected to the power line. A housing supplied with the equipment, which may also contain the motor-generator unit, contains a water-cooled capacitor, C, and output terminals. The connecting leads, T, and the coil, W, complete the installation. Other common arrangements, such as with the capacitor located at the coil, will be considered subsequently.

As noted in the discussion of principles, the rate of heat generation in the work is greater for a stronger magnetic field, and the field strength for a given coil depends on the amount of coil current times the number of turns in the coil. Therefore, the greatest current possible is desired for a given coil and circuit arrangement.

Realization of High Coil Current

The amount of current in a coil can be calculated by using Ohm's law for the coil. That is

$$I=\frac{E}{Z}$$

where

I=the current in the coil in amperes
E=the voltage applied to the coil, in volts
Z=the electrical impedance of the coil in ohms.

The impedance, Z, of the coil depends on the geometry and composition of the coil and physical properties of the workpiece, assuming a given frequency. Temperature may affect several of these factors, especially those of the workpiece. Once the geometry, composition, and frequency are chosen, the direct way to obtain high current in the coil is to apply a high voltage.

A common output voltage for a commercial motor-generator set is 440 volts. A common frequency is 10 000 Hz (10 kHz). The impedance of a work coil used for a 10-kHz induction heating application could be as low as 0.2 ohm. By Ohm's law, and assuming 440 volts available at such a coil, one would expect a current flow of 2200 amperes. However, a generator capable of delivering 2200 amperes on a continuous basis would be large and expensive. To realize this large current in the coil while drawing only a relatively small current from the generator, the "resonance principle" is used. Resonance can be explained conveniently with the aid of figure A–7, which shows another common arrangement (an alternative arrangement to figure A–6) with the capacitor at the coil instead of at the generator. The capacitor, C, of figure A–7 is connected in parallel with the work coil, W, and energy from the generator is supplied via the transmission line, T. If the capacitor is the proper size to resonate with the inductance of the coil at the frequency of the generator and with the workpiece in place, a special circulating energy condition occurs. For half a cycle of applied voltage, electrical energy flows from storage in the capacitor into the coil to establish a magnetic field. For the other half of a cycle, the energy stored in the magnetic field flows back into the capacitor. The amounts of energy thus circulating can be very large if the losses are small, giving rise to very large currents flowing into and out of the capacitor and through the coil. The generator, however, has only to make up the energy lost during the process, normally requiring a relatively small current such as 100 amperes. This combination of coil and capacitor is often referred to as a "tank" circuit.

In a parallel resonant circuit with the capacitor in parallel with the coil, as shown in figure A–7, the current within the resonant circuit is approximately Q times the current supplied by the generator. Q is

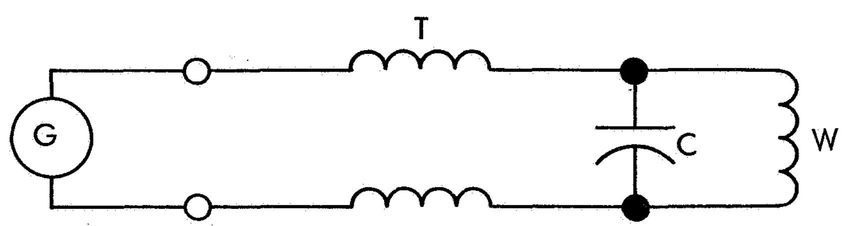

FIGURE A–7.—Arrangement of components with capacitor located at load.

the quality factor of any component, usually defined for a resonant circuit, as

$$Q=\frac{2\pi fL}{R}$$

where f is frequency in hertz, L is the inductance of the coil and workpiece in henries, and R is the resistance at the coil terminals in ohms. Q is also equal to 2 times the ratio of peak stored energy to dissipated energy per cycle in a coil. Since the capacitors used have very low losses, any effect of the capacitor on the Q of the resonant circuit is usually ignored.

The power factor can be used to measure how close to the resonance condition a circuit is operating. The power factor is defined as the cosine of the electrical angle between the applied sine-wave voltage and the resultant sine-wave current flow. When the angle is zero, cos=1.0 and unity power factor (resonance) is achieved. With a coil alone connected across the generator, coil current will lag the generator voltage in electrical angle and the generator will not be effective in producing heat. With a capacitor alone across the generator, the current leads the voltage. With both a coil and the correct capacitance to produce resonance, the current and voltage supplied by the machine are in phase, and the phase angle is very small, or zero. The capacitor then is acting to change a low impedance, consisting almost entirely of inductive reactance and hence having a low power factor such as 0.1, into a higher impedance that is neither inductive nor capacitive, but resistive with a power factor near unity.

It is found that at resonance, the voltage appearing across the coil can amount to the full 440 volts mentioned previously, giving the 2200 amperes of coil current. (This current circulates in the coil-capacitor circuit.) The current needed to accomplish this as measured at the generator, however, may be only 100 amperes, which is entirely within the capabilities of the machine.

The energy-storing capability of a capacitor is measured in terms of kva (kilovolt-amperes) which is calculated as the voltage rating of the capacitor in volts times its current-carrying capacity in amperes, divided by 1000. The total capacitance required for resonance (or unity power factor) in the example used above, therefore, would be approximately 440v times 2200 amperes, divided by 1000, or 960 kva. The actual capacitors themselves frequently are supplied in units of 200 or 300 kva each, several of which can be connected in parallel as needed. Each capacitor unit will offer about 4 to 8 tap connections to permit the user to obtain finer subdivisions of the total capacitance by connecting part or all of the taps into the circuit.

Inductive Voltage Drops

With the arrangement shown in figure A–6, which is quite common in small commercially available equipment, the 2200 amperes referred to must circulate from inside the housing of the equipment along the connecting line T, through the coil W, and back along the line. Considerable loss of voltage can thus occur because the transmission line has inductance.

Inductance can be considered as a property relating to the ability of a device to store energy in a magnetic field (while capacitance relates to the ability of a device to store energy in an electric field). When a circuit such as a connecting line has inductance, it also follows that a certain voltage drop will occur per unit length along that line when one passes alternating current through the line. This can result in the voltage reading across the coil being, for example, only 300 volts while the generator still supplies 440 volts. In this case, the current realized in the coil (and the entire external series circuit) using the above example would be

$$I = E/Z = 300/.2 = 1500 \text{ amperes.}$$

Therefore, the heating ability would be only $(1500/2200)^2 \times 100$ percent or some 45 percent of what it was formerly. Clearly, one should try to achieve a relatively low inductance in connecting lines. Another approach is to place the capacitors at the load (see fig. A–7) so as to require much less line current. Other arrangements and ways to reduce detrimental voltage drops in the connecting lines will be considered in greater detail in a following section.

The importance of the properties of the connecting line is suggested in the above example. Other important effects that govern the degree of success are involved with the generator and the work coil. Several requirements for good design and operation of an induction heating installation are summarized in the following section. Additional explanation will then be presented, including examples from the experience of the Lewis investigators. By careful consideration of the requirements, the user will be better able to examine his installation objectively to determine likely areas for improvement.

Requirements and Procedures in System Design and Operation

The following requirements and guidelines to procedure are subdivided as much as possible to fall into the three main portions of an installation as described above: generator, connecting line, and coil. These are the *principal operating and design conditions*, in regard to equipment, that should be considered to obtain the best results in induction heating.

Generator

Generator operation is discussed primarily as it pertains to the motor-generator type of equipment. However, many of the same requirements also apply to radio-frequency and other power supplies.

Adequate Power Rating.—Although this item is listed first, inadequate generator power rating is not necessarily the most likely explanation of failure to obtain desired induction heating performance. The reader is urged to make a systematic examination of all the principal factors that might be responsible for less than the expected performance, before taking major steps to change generator rating. It is often true that the heat losses from a workpiece are sufficiently great to limit the maximum available temperature for a given generator. A good estimate of heat loss can often be obtained by calculation. Reduction of heat losses can then provide significant improvement.

Motor-generator equipment is rated on the basis of output. That is, the equipment is able to produce enough power to supply its own internal losses and still deliver rated power at its output terminals, assuming the load is within the range for which the equipment is intended. When the needed power exceeds the rating of an available generator it may be possible to connect a second machine in parallel with the first to obtain more power.

Theoretically, any two or more motor-generator units regardless of their individual output capacities can be connected in parallel, provided they are of the same frequency. However, the operation is not efficient, that is the load will not be evenly divided, unless the units are identical, or nearly so, in many characteristics. This is so important that, whenever units are intended for paralleling, they should be so designated when they are ordered so that special engineering and testing procedures may be followed. More specifically, the following factors must all be observed:

(1) Speed versus load characteristics of the motors must be identical. If one of the motors loses speed more rapidly under load, it is obvious that the load will not be shared by the generators. This is most important at full capacity

(2) The motors must be connected to the same power supply. This is to assure that the same voltage is applied to each unit regardless of other plant electrical loading conditions

(3) The output ratings of the units must be identical as to voltage, current, power, and frequency

(4) Field current should be supplied and controlled from a single source so that identical field changes are made in all units simultaneously

(5) There is no need to be concerned over phasing controls, because with squirrel-cage induction motors the generators will automatically synchronize.

A single tank circuit normally would be used for the parallel-generator application. For proper matching to the generators (see below), the impedance of the optimum tank circuit would be half the optimum impedance for a single generator. Although the paralleling procedure is not complicated, to reduce risk of damage it is recommended that the advice of a specialist be obtained at least when making the initial connection.

Matching the Load to the Generator.—If the full power rating of a generator is to be realized, it is essential that the electrical conditions of the installation be such that full rated current is drawn from the generator when it is set to deliver rated output voltage, and that approximately unity power factor be indicated by the instruments. The achievement of this condition is referred to as "impedance matching." This means that the load condition is such that the power supply can deliver its maximum design energy, *not* necessarily that the impedance of the load equals the internal impedance of the supply. Because of the importance of this procedure and because of certain steps taken when using transformers, matching is considered in a special section following.

Over-ratings.—The power, voltage, and current ratings of a generator are selected to permit continuous use at these values for long periods. The machine capacity is limited by the maximum permitted temperature rise of the most critical component, and by voltage breakdown of the capacitor or machine insulation. In some cases, current overload of 50 percent or more is possible for short periods of several seconds, followed by periods of reduced load, without danger to the equipment. The operation at overload requires a knowledge of temperature limitations of the most critical component, and respect for insulation ratings. Except for a 10 percent or 15 percent overload for short periods, overloading should not be attempted without professional advice or the manufacturer's guidance.

Connecting Line

The connecting line between the generating equipment and the work coil serves in one of two manners. (1) It serves to deliver the relatively low generator output current to the tank circuit as in figure A–7, in which case the tank capacitor, *c*, is located near the work coil. (2) It serves as an extension of the work coil itself as in figure A–6. In the latter case, it must carry several times as much current as in (1), and therefore the design of the line is most important.

Low Series Impedance.—The connecting line should offer low series impedance to the flow of current at the operating frequency, especially for the system of figure A–6. At motor-generator frequencies, the series impedance of the connecting line will consist mostly of inductance; the inter-conductor capacitance will shunt very little current and so can be ignored.

Since the series impedance is mostly inductance, it can be reduced by using lines with proper configurations. Low series inductance can be realized by (1) using close physical spacings between the outgoing and return conductors, (2) using conductors that have large areas facing one another, such as parallel bus bars, or (3) using multiple conductors.

Closely spaced bus bars are commonly used for high current conditions. Bus bars are the preferred approach for the coil leads where the current is the highest of any portion of the system. Here $\frac{1}{4} \times 4$ inch bars, or $\frac{1}{8} \times 6$ inches, spaced from 1/32 to $\frac{1}{4}$ inch have served adequately for loads up to 70 to 80 kw at 9600 Hz without water cooling. Much higher power can be transmitted with water cooling. At bends that must be made in a direction in the plane of the bars, a convenient approach is first to twist the bars 90° and then the bend can be made easily without having to construct flat elbows.

In connecting from bus to coil or one conductor to another, conventional dc welding connectors have been found to work well if any steel set screws or keeper rings are first replaced by nonferrous substitutes such as brass. Bus bars in the coil circuit should be provided with water-cooling channels or tubes silver soldered to the exterior faces of the bars.

Where long runs, such as 100 to 150 ft, separate the generator and the tank circuit, low inductance design for the connecting line such as the use of small spacings between outgoing and return conductors becomes especially important. In this case, a multiconductor cable has been found useful. A load of 75 kw has been fed by means of a 22-conductor cable of insulated No. 9 conductors. Success was achieved without following any particular pattern for connection of the conductors by polarity. However, preferred practice would be to have a plus and minus conductor as close to side-by-side as possible. The power was transmitted at 440v over a 100-ft run in one case with only a 20-volt loss. No water cooling was used for the multiconductor cable. Note that the generator current rather than the tank current is involved in this case.

Flexible water-cooled leads are available commercially. In high-current circuits these should be conservatively rated and used with multiple strands at low spacings. Substitution of $\frac{1}{4} \times 6$ inch bus spaced

$\frac{1}{16}$ to $\frac{1}{32}$ inch for a 4-foot run of flexible leads in one 50-kw application reduced the voltage drop from 90 volts to 10 volts. However, efficient circuits using water-cooled leads also can be arranged.

Successful feed-through insulators have been made for bus bars to carry high currents through the walls of protective-atmosphere chambers. Bonds between the water-cooled bus and bakelite or formica plates can be made by means of low-vapor-pressure cements. The plates are sealed to the wall by means of O-Rings.

High Transmission Voltage.—As with cross-country power transmission, increased efficiency is realized by transmitting electrical energy at the highest practical voltage. Use of a transformer at the end of a line, as discussed below, brings the voltage down, and current up, for connection to the work coil. Transmission at high voltage is efficient because, since power equals the voltage times the current, a given power transmitted at higher voltage requires lower current. Lower current means that smaller line conductors can be used for a given power dissipation. For a given line of a given series impedance, the flow of a smaller current will produce a smaller voltage drop along the length of that line. With the smaller voltage drop, more of the voltage output of the generator will be available at the transformer and work coil, permitting better utilization of the generator and a more effective coil and transformer performance. Some industrial plants use a high-frequency distribution system at generator voltage levels to deliver power from a central generator to several work stations which may be separated by hundreds of feet.

Work Circuit

The work circuit refers to the coil, or inductor, in which the work is placed for heating, the connecting leads which are an extension of the coil, the capacitors which serve to resonate the load, and any transformers which may be used to increase the coil current.

Coupling.—To produce large currents in the workpiece effectively, the spacing between the work coil and the work should be as small as practical. A clearance of $\frac{1}{4}$ to $\frac{1}{2}$ inch usually represents a suitably small spacing from the coupling standpoint, but other factors such as arcing at high temperatures and mechanical problems may require greater clearance. Greater clearance or coil insulation would be recommended for higher voltage machines such as arc, spark, or vacuum-tube power sources. Small clearance is more important on small-diameter workpieces and in some cases may be only a few thousandths of an inch.

Since the rate of heat generation depends on the coil ampere-turns per inch, it is also important to provide only a small spacing between turns. Using a small tubing size to construct a coil can provide good performance, but a limit is reached where the reduced water flow limits the cooling action with possible damage, or the resulting increased electrical resistance of the smaller tubing reduces the efficiency.

Coils and Transformers.—Work coils for induction heating must carry large currents and fit into relatively small spaces. The magnitude of the current normally carried by a work coil is easily sufficient to melt the coil in a short time, unless sufficient cooling is employed. This requirement is usually met by means of water cooling of the coil. The coil leads as well as the capacitor and other elements of the tank circuit also carry large currents and probably will require water cooling.

The same tendency for skin effect to occur in a load, as described previously, also takes place over the cross sections of the conductors of the work coil. This skin effect leaves low current concentrations at the center of each conductor. This center space, therefore, is often used as a channel through which cooling water can be passed. This is accomplished by making the work coil of copper tubing with water flowing through it. Square or rectangular water-cooled tubing is often used for coil construction.

Since water cooling is required, the cross section of the tubing from which the coil is made must be sufficiently great to permit adequate water flow. This may amount to several gallons per minute in some cases. Clearly, a physically large tubing cross section will not permit very many turns per inch in winding a coil. Further, the coil should not be very much longer than the workpiece for best efficiency of heating. These factors act together to create the problem of how to achieve a high value of ampere-turns per inch, especially since the heating rate is proportional to the square of the ampere-turns per inch of coil length. A coil of few turns simply requires more current to achieve the high rate of heating of which the generator is capable. High current can be obtained with the aid of a transformer, as described below.

Almost always when the small size of the work limits the work coil to a few turns, a transformer is required to provide the necessary high current to the coil and permit realization of the full ability to obtain heating. A common arrangement of equipment using a high-frequency transformer with core to feed the work coil is shown in figure A–8A, in which the transformer is denoted by an X.

While providing high current to the coil, the transformer also acts to provide an impedance match to the generator. As discussed earlier, a low impedance coil connected directly to the generator would act much like a short circuit and rated current would be drawn from the generator for only a few volts of output. Full generator power would

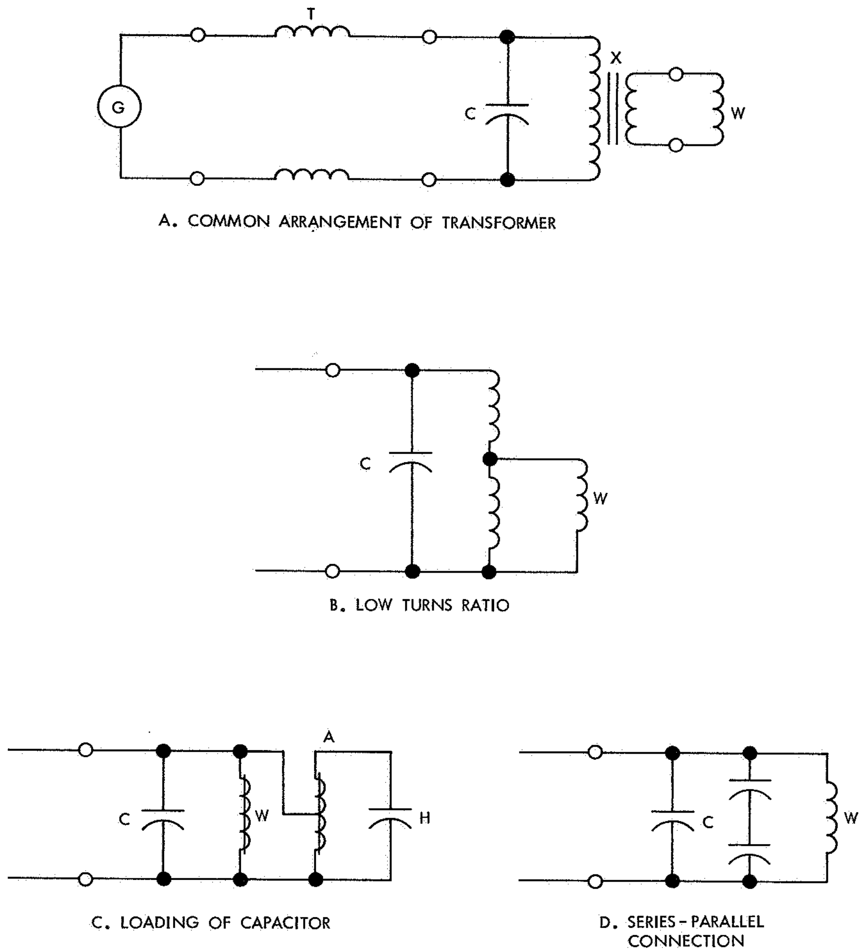

FIGURE A–8.—Arrangements of transformers and capacitors.

not be realized in the workpiece. Although some benefit could be realized by a large increase of the tank capacitance, C, to approach unity power factor for the small coil, this would involve great expense and still probably would not provide full power in the workpiece. The transformer, however, provides the means for converting the low impedance of the coil to a higher impedance suitable to fully load the machine. At the same time, the capacitance needed is now only the usual size.

The best load conditions for the generator for a given coil can be achieved by selecting the proper turns ratio for the transformer. Transformers with a range of available turns ratios can be purchased commercially, and will serve to convert a great variety of coil sizes and shapes into an ideal load for a given generator. The procedure for finding the best turns ratio and best capacitance size for a given setup are considered below in the special section on matching.

When an available transformer does not offer a sufficiently wide range of primary taps for selection of turns ratios, additional taps on the winding can be silver soldered into place. Fixed-ratio transformers can thus be converted to provide a variable ratio. Also, on occasion, it is convenient to make use of low turns ratios such as 2:1. This can be obtained by placing a center-tap on the primary winding and using the primary winding as an autotransformer such as is shown in figure A–8B. The secondary winding is either removed completely or not connected.

A warning should be given in regard to low-turns-ratio transformer connections. Many transformers for induction heating have only 1 or 2 turns on the secondary winding. A two-to-one ratio with only one turn on the secondary would mean only two turns on the primary winding. For any application other than very low power, considerable risk of damage to the transformer would be involved in connecting such a primary winding to the generator. The risk occurs because these transformers are designed for low flux density. With fewer turns on a winding, too much flux will develop in the core at low voltages, leading to magnetic saturation of the core. Upon saturating, the transformer impedance will no longer limit current flow from the generator, and waveform distortion becomes severe. The higher current and distorted waveform produce heat in the core which may damage the transformer. Therefore, a low-turns-ratio autotransformer should be acquired for this purpose or constructed as suggested in the previous paragraph. Manufacturer's specifications usually indicate the minimum number of primary turns permitted for a given transformer size.

Transformers for induction heating are rated in kva of input. The kva rating is approximately equal to the kva rating of the capacitors needed to resonate the circuit. Transformers with larger core cross sections can handle more power. The manufacturer's recommendations should be observed since a given core size can handle different powers at different frequencies.

Induction heating transformers are usually water cooled and are intended to operate at moderate efficiency. This and the fact that they operate at high frequency permits them to be only a fraction of the physical size and cost of conventional distribution types for a given power-handling ability.

Capacitor Arrangements.—Conventional means for connecting the tank circuit capacitors are shown in figures A–6, A–7, and A–8A. The method of figure A–8B was mentioned previously.

Capacitors for induction heating are generally rated by ac voltage, frequency, and kva. It is not a good practice to operate a capacitor above the voltage rating at rated frequency. Besides the danger of a breakdown of insulation, more ac voltage applied means more current flow through the capacitor, which would result in overheating. As with conventional capacitors, however, two capacitors of equal capacitance rated at a given voltage can be connected in series to provide half the capacitance at twice the voltage. The combined kva rating in this case would be the sum of the two lower voltage kva ratings. An arrangement of one normal capacitor connected in parallel with the series combination of two lower voltage capacitors is shown in figure A–8D.

If a given capacitor is available having a higher voltage rating than the voltage of the circuit, it will not provide rated kva at the reduced voltage. In this case, better use sometimes can be made of it by driving it with a step-up transformer, shown in figure A–8C, so as to provide rated voltage to it. The high-voltage capacitor is noted as H, and the step-up autotransformer as A in figure A–8C.

Tank capacitors for use in induction heating, where transformers are used with a work coil of only a few turns, are almost always connected on the primary side of the transformer. The voltage on the secondary side usually is too low to permit any advantage from a practical capacitor. This is sometimes not true for higher frequency applications.

Low-Impedance Design.—Current levels are particularly high in the connecting lines between a transformer secondary winding and a work coil. This means that the steps described previously for maintaining low series inductance, such as the use of close spacings between buses and wide bars, are particularly important. The best way to assure low voltage loss at this point is to use very short runs, placing the transformer secondary terminals as close as possible to the work coil.

Water Cooling

Because of the skin effect present with high-frequency currents in conductors, and because of the large magnitude of currents employed, forced cooling is customarily used to avoid overheating of the current-carrying components of induction heating installations. As has been described, water cooling is generally used for coils, capacitors, and connecting lines. The generators employ forced air, which is frequently recirculated through water-cooled heat exchangers that can comprise portions of the generator housings.

In order to help assure that induction heating equipment is operated only with proper cooling, water-flow protective switches or pressure switches in the drain lines are used. Temperature cut-out switches for air and water are also employed as interlocks. In some cases, some water circuits in use may not be protected with switches. In any instance, an added measure of safety can be achieved by using a "sight drain" in which all drain lines discharge visibly into a common drain trough. The operator can then actually see water discharging from each water circuit before energizing the electrical equipment.

One of the easiest ways to make a costly mistake in operating induction heating equipment is forget to turn on the water. The proper protective procedures can reduce such damage to a minimum.

Special Section on Matching

The benefits to be achieved by proper "matching" are great, for the matched condition permits the full generating capacity of the equipment to be converted into heat. The procedure and its explanation can be complicated to the layman. For these reasons, the user is urged to study this section carefully.

The objective in matching the load to the generator is to arrange the circuit so that when full voltage is delivered by the machine, full current is being drawn, and the kilovar (KVAR) meter is reading nearly center scale. In fact, much modern equipment has meters calibrated in percent of rated output rather than volts, amperes, kilowatts, and kilovars.

As was discussed in the section on realization of high coil-current, the purpose of the tank capacitance is to resonate the work circuit so that a large circulating current is achieved through the work coil without having to draw this high current from the generator. The kilovar meter associated with the generator reads center scale on a zero-center-scale meter when the capacitance is just right to resonate, or tune the work circuit. When the capacitance is too large, an abnormally large amount of current will be drawn from the generator and the kilovar meter will read in the lead (corresponding to the condition for current leading the voltage in electrical angle). When the capacitance is too small, too much current also will be drawn with the kilovar meter now reading in the lag for lagging current. The current and impedance relationships are shown in figure A–9 for conditions near resonance. The unusual curve is included to show the effect of changing capacitance.

Confusion arises when the capacitance is considerably off-size. In this case so much current is likely to be drawn that the ammeter reads full scale with a much lower generator voltage output. With such a low voltage output, the kilovar meter cannot function properly. This is true with this type of meter, as with watt-meters, since the meter acts to compare or multiply a voltage and a current input. If one input

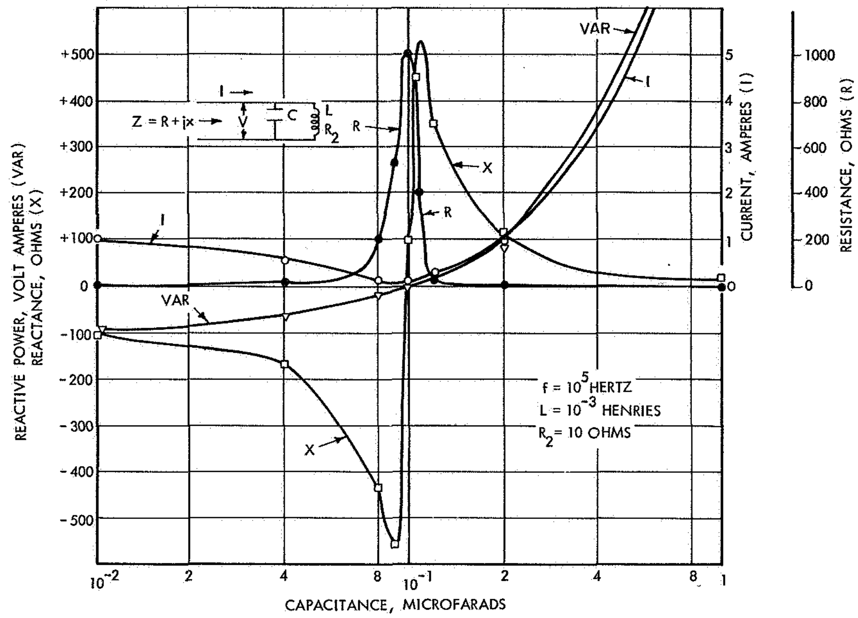

FIGURE A–9.—Characteristics of resonant circuit with voltage constant and power constant.

is too low, then no meaningful output indication is possible. If this situation occurs to the degree that one cannot tell whether to increase or decrease capacitance to approach resonance, one expedient remedy is to disconnect all capacitance and start adding it back in steps with frequent trials until a meaningful indication is obtained.

The above procedure usually permits the resonant condition to be found. However, a resonant condition is no assurance that the impedance match is proper. It is often true that the load impedance is too low (unable to realize full output voltage) or too high (unable to realize full output current) even though the power factor may be unity. The steps to be taken next depend on whether or not a load transformer is used to connect to the coil. These two cases are considered separately.

No Transformer.—For this case it is assumed that the work coil is connected directly to the generator or to a connecting line. If the load impedance then is too high, turns can be removed from the coil to decrease the impedance. It may then be necessary to open (increase) the turn spacing to maintain heating over the full length of the workpiece. Opening the spacing will also reduce the coil inductance. Another approach to reducing the impedance of the work coil-connecting line combination is to reduce the spacing between any conductors leading to the coil. On the other hand, if the load impedance is too low, turns can be added, or turn spacing decreased, or the lead spacing increased.

In some cases when a work coil of very small inductance must be used and where efficiency is not paramount, an auxiliary inductance consisting simply of an unloaded work coil can be connected in series between generator and work coil. The auxiliary coil permits unity power factor to be achieved without a transformer, thus permitting delivery of at least some power to the load which could not have been realized otherwise.

With a Transformer.—The use of a load transformer which offers a choice of several turns ratios will often permit proper generator matching without need to modify the coil or the connecting leads. However, the proper adjustment of *both* the turns ratio and the tank capacitance must be made to achieve good matching.

If the transformer turns ratio differs considerably from the optimum, an excessive current condition can occur that cannot be detected easily from an improperly sized capacitance. To determine the proper transformer ratio, the circuit should first be brought to unity power factor by adjusting the capacitor. The relative current and voltage values can then be interpreted as follows:

If, as the machine power is increased, the machine voltage reaches full rating before the ammeter does, the primary-to-secondary turns ratio is too high. Conversely, if the current reading reaches full rating before the voltage reading does, the turns ratio is too low. Upon making a correction of turns ratio in the direction indicated, it will be found that operation is no longer at unity power factor. The proper step then is to *readjust* the capacitance to unity power factor before interpreting the voltage and current readings for further turns ratio adjustment. If this combination of steps is repeated a few times, the reward will be a much higher rate of heating.

Once the nearly matched condition is reached it may be found that even greater heating rate can be realized by operating with a slightly leading power factor (capacitance higher than that for unity power factor).

One of the most frustrating but readily overcome problems is this process of matching the load to the generator. The above suggestions should help in achieving satisfactory operation without the aid of a specialist. Additional information on impedance matching is presented in the ASM Handbook, 8th Edition (ref. A–7) as well as in other references cited in this text.

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